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Structure in the velocity space of globular clusters

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Abstract. We present an analysis of the velocity space of a sample of globular clusters (GC) with absolute proper motions. The vertical component of the velocity is found to be correlated with luminosity and galactocentric radius. We divided the sample into two luminosity groups above and below the peak of the luminosity function (LF), $M_V = -7.5$, for Galactic GCs. The two groups display different kinematic behaviour according to the first and second statitical moments of the velocity distribution as well as distinct velocity ellipsoids. The velocity ellipsoid of the high luminosity clusters is aligned with the symmetry axes of the Galaxy, whereas the minor axis of the Low Luminosity group is strongly inclined relative to the Galactic rotation axis.

Key words. Galaxy: formation – Galaxy: globular clusters: general – Galaxy: halo – Galaxy: kinematics and dynamics – Galaxy: structure

1. Introduction

It has been known since the late eighties that groupings exist in the velocity space of several halo tracers which could be interpreted as debris from larger stellar sub-structures disrupted by the Galaxy (Sommer–Larsen & Christensen 1987, Dionidas & Beers 1989, Arnold & Gilmore 1992, Poveda et al. 1992). In particular, some kinematic studies of halo stars (Majewski et al. 1996, Chen 1998) indicate that the Galactic halo may not be a dynamically relaxed system. The presence of three moving groups in the SA57 field near the NGP, with different metallicity distributions, supports the hypothesis that the Galactic halo is mainly formed from a mixture of several stellar streams.

Analysis of the radial velocity dispersion tensor of the GCs (Hartwick 1996) also falls upon the idea that the Galactic halo is not dynamically homogeneous. Two different subsystems are clearly identified in that study; one, located in the outer region of the halo ($R_g > 7$ kpc), shows a minor axis parallel to the Galactic rotation axis, while the second inner one is highly inclined relative to the symmetry axes of the Galactic disk. The fact that the inner Galactic GCs present a velocity ellipsoid almost parallel to the spatial distribution of the outer satellites suggests that the outer satellites may be outlining the Galaxy's dark matter halo and that the actual residual velocity distribution of the inner halo clusters might be representative of the dominant potential well in the early phases of the halo formation (Hartwick 2000). Thus, there is evidence in favor of two peculiar kinematic features in the halo: 1) miss-aligned residual velocity ellipsoids and 2) moving groups whose origin might be ascribed either to "pollution" by disrupted satellites or to the signature of the early dominant potential well.

Another interesting peculiarity of the Galactic globular cluster system is its present LF. In contrast to disk open clusters that show a monotonically increasing LF, globular clusters show a peaked distribution with a maximum around $M_V \approx -7.5$. Some authors consider this LF to be primordial (e.g. Fall & Rees 1988, Fritze-von Alvensleben 1999) while the most accepted interpretation supposes that the present distribution evolved from an initial power-law distribution through destructive processes (Larson 1996, Elmegreen & Efremov 1997). Dynamical modelling of halo globular clusters in the Milky Way potential shows that destructive processes, and their time scales, depend strongly on orbital parameters and cluster masses (e.g. Capuzzo-Dolcetta 1993).

Following these arguments, we ask to what extent kinematics and luminosity (and hence mass) are correlated and, if correlated, how this reflects on the velocity space of the GCs. In this respect, the work by Burkert & Smith (1997) indicates that the metal-rich GCs can be separated by mass into three groups, with different spatial and kinematic properties. Here we present a similar analysis for

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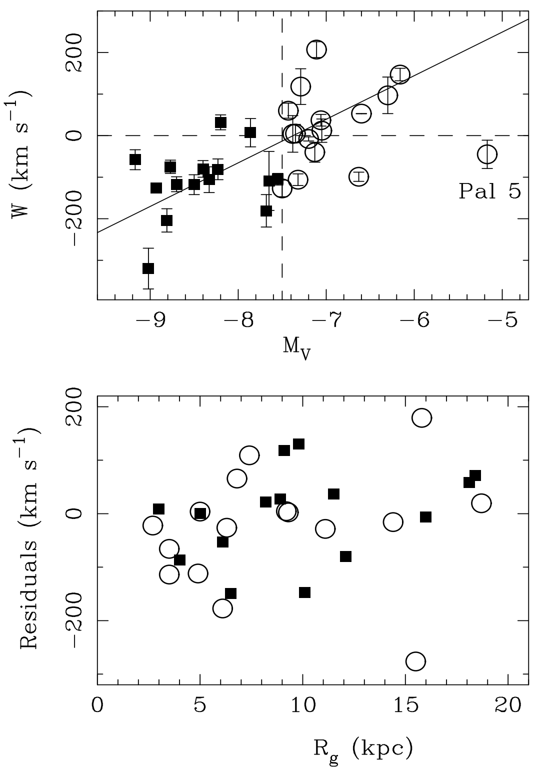

Fig. 1. (*Top panel*). Vertical component of the velocity versus M_V for the sample of halo GCs with complete kinematic information. Open circles represent the clusters with $M_V \geq -7.5$ and black squares those brighter than M_V=−7.5. Note that most of the clusters appears located in two of the four quadrants in which has been divided the plot. (*Bottom panel*). Residuals of the linear fit shown in the top panel versus galactocentric distance.

the metal-poor GCs and study the velocity space of the halo GCs with complete kinematic information.

The paper is organized into three main sections. Section two is devoted to a description of the sample and presentation of our results while the final section considers possible interpretations.

2. Kinematics and Luminosity

2.1. The sample

Our data sources are the compilation of absolute proper motions for GCs (Dinescu et al. 1999; DGA in the following) and the updated version (June 1999) of the catalogue of "Milky Way Globular Cluster Parameters" by Harris (1996). The first compilation provides information about the velocity components and orbital parameters, as well as metallicity, radial velocity and spatial information for 38 Galactic GCs (the largest sample so far with complete kinematic information). The second one provides a large set of physical, structural and photometric parameters, including total luminosity, for the entire Galactic globular cluster system. Errors in velocities have also been taken from DGA, who adopted a 10% error in the distances. The average uncertainty in the integrated absolute magnitudes is ≈0.5.

We limit our study to the halo GCs within a galactocentric radius of 20 kpc. Thus, two clusters with [Fe/H]≥ −0.9, typical of the disk sub-system, and Pal 3 located well beyond our limit radius, have been removed. Three other clusters (NGC 6254, NGC 6626, and NGC 6752) display disk-like orbits and can be considered to be the metal-poor tail of the disk sub-system (DGA). NGC 5139, in addition, is thought to be the core of a disrupted dwarf spheroidal galaxy (Majewski et al. 2000). These four clusters are consequently omitted from our analysis. The final kinematic sample contains 31 "bona fide" halo GCs representing ≈40% of the halo cluster population within 20 kpc. This sample distributes with metallicity, total luminosity, and galactocentric radius in a rather similar way to the ones shown for the halo cluster population inside the same volume. The main difference involves the R_g variable whose distribution is flatter than the typical potential law shown by the halo GCs.

The kinematic data are considered in a cylindrical coordinate system. The Π component is positive outwards from the galactic center, whereas the other components retain their usual conventions; Θ is positive towards the direction of galactic rotation and W towards the North galactic pole. The centroid and dispersion of the velocity components for our sample [($\langle\Pi\rangle$=25±25, $\langle\Theta\rangle$=50±16, $\langle W\rangle$=−43±21); (σ_Π=137±23, σ_Θ=100±13, σ_W=107±21)] present a mean rotational value similar to the ones obtained from radial velocity data for the metal-poor globular clusters (Côté 1999). The present values of the velocity dispersion are in good agreement with those obtained by other authors for halo stellar samples (Norris 1986, Morrison et al. 1990). Thus, on the basis of rotation and velocity dispersions, the sample can be considered as representative of the halo globular clusters.

2.2. Velocity components versus Luminosity

We began our study by analyzing the distribution of the velocity components with luminosity for our sample. The vertical component (W) is plotted versus the integrated absolute magnitude (M_V) in fig. 1 (top panel). A clear correlation is apparent in this plot, which translates into a probability lower than 0.1% that the two variables are uncorrelated (τ-Kendall and Spearman tests). Only the lowest luminosity cluster in our sample, Pal 5, separates from the main distribution. This cluster is representative of a small group of faint objects located beyond R_g=10 kpc which do not have a counterpart in the inner galactic regions (McLaughlin 2000). It has been suggested that this group of clusters formed more recently than the rest (van den Bergh 1999, private communication to MacLaughlin). Fig. 1 (top panel) also shows a robust linear fit to the data while the residuals of the fitting are plotted against galactocentric radius in the bottom panel of fig. 1, where

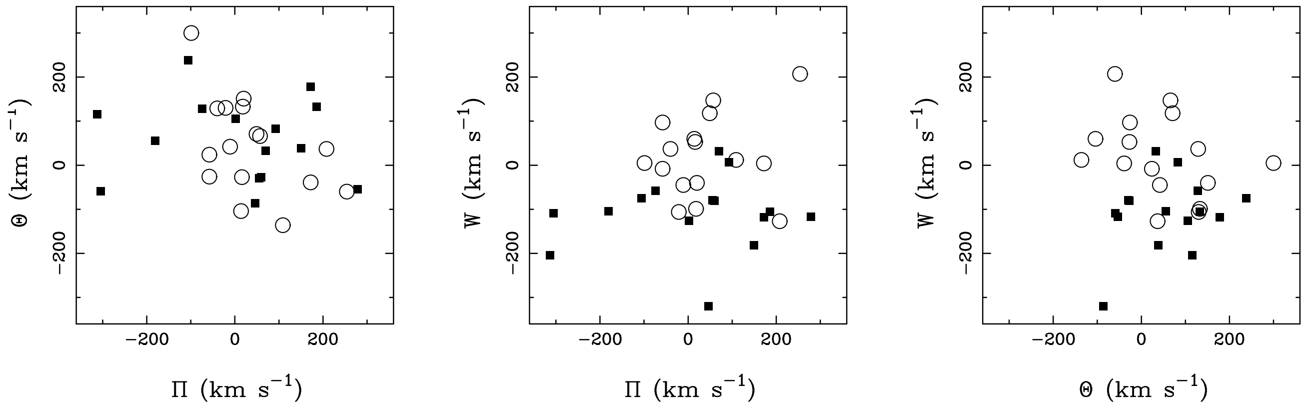

Fig. 2. Distribution of the halo globular clusters with complete kinematic information onto the main planes defined by the cylindrical velocity components. Symbols as in fig. 1.

a weaker but apparent correlation (probability lower than 7% that the two variables are not correlated according to τ-Kendall and Spearman tests) is also present. These results indicate that for halo clusters with integrated absolute magnitudes between −9.2 and −6.0, the vertical component of the velocity scales with luminosity and, marginally, with galactocentric radius.

The other velocity components do not clearly correlate with luminosity although, as we will discuss in the next sub-section, clusters with different luminosity display distinct kinematic behaviours.

2.3. Luminosity Groups

Our sample has been divided into two groups according to their integrated absolute magnitude. There are 15 clusters brighter than M_V=−7.5, which form the *High Luminosity Group* (HL) while 16 constitute the *Low Luminosity Group* (LL). The first and second moments of the velocity distribution have been estimated for both groups and the mean radial component shows a marginal difference between the HL and LL clusters (9±40 and 39±24 respectively), where the LL group shows evidence for a weak expansion. The mean rotational moment (57±24 and 43±28 for HL and LL respectively) is similar for both groups and also agrees with the average value obtained for the metal-poor GCs from radial velocity data (Côté 1999).

The main difference involves the vertical velocity component where 13/15 of the HL clusters display negative values of W and an average vertical component of −109±21. In contrast, the mean value for the LL group is 20±23, where 10/16 objects show positive W values. A Kolmogorov-Smirnov two-sample test gives a probability lower than 1% that both sub-samples come from the same population.

Fig. 2 shows the velocity space for our data, projected onto the three principal planes defined by the cylindrical velocity components. This plot reveals that the luminosity groups distribute in a different way: 1) the radial component of the HL clusters (black squares) display a wider range of values than the LL group (open circles) and 2) the (Π, W) plane distribution of the LL clusters is highly inclined relative to the Galactic rotation axis. The velocity dispersions for the LL and HL clusters are (σ_Π=168±32, σ_Θ=92±15, σ_W=81±17) and (σ_Π=97±19, σ_Θ=107±21, σ_W=90±17) respectively.

In order to analyze in more detail the velocity space of these groups, we have derived the velocity ellipsoid for both distributions. The evaluation procedure has been configured in a bootstrap loop in order to provide an estimate of the parameter uncertainties. Table 1 shows the module and direction of the three main axes of the two distributions. The velocity ellipsoid defined by the distribution of the brightest clusters is almost parallel to the principal axes of the Galaxy, while the Low Luminosity objects distribute in a highly inclined ellipsoid.

Table 1. Velocity ellipsoids for the two groups of luminosity, σ is given in km s^{-1} and the Galactic coordinates, defining the direction of the main axes, in degree. The estimated errors are the dispersion of 100 bootstraped samples.

HL			*LL*		
σ	l	b	σ	l	b
151 ± 21	10 ± 40	6 ± 9	105 ± 14	−63 ± 50	45 ± 32
130 ± 21	−80 ± 42	4 ± 26	102 ± 14	40 ± 40	13 ± 31
80 ± 15	−137 ± 58	83 ± 29	50 ± 11	−38 ± 24	−42 ± 43

3. Discussion and Conclusions

The analysis performed in the previous section provides evidence for a clear connection between kinematics and luminosity which can be summarized as follows:

1. The vertical component of the velocity (W) scales with luminosity and galactocentric radius for a sample of 31 metal-poor GCs with absolute proper motions.
2. The sample of globular clusters has been divided into two absolute magnitude groups separated above and

below $M_V=-7.5$. The first and second statistical moments of the velocity distributions of the groups show significant differences.

3. Both luminosity groups display different structure in the velocity space. The velocity ellipsoid of the High Luminosity group is aligned with the main axes of the Galactic disk while the Low Luminosity clusters show a velocity ellipsoid with minor axis highly inclined with respect to the Galactic rotation axis.

The first result is very surprising and we have no satisfactory explanation for the existence of such a relationship between vertical velocity and luminosity. Given that our kinematic sample represents 40% of the halo population in this volume, we consider whether this correlation could be produced by a selection effect involving the clusters with absolute proper motions. In order to check this we have taken the complete set of halo GCs within 20 kpc and estimated the average vertical component for the two luminosity groups using only radial velocity data. Assuming the system has neither net expansion nor rotation, we obtain ($\langle W\rangle^{HL}=-32\pm6$; $\sigma_{los}^{HL}=115$) and ($\langle W\rangle^{LL}=46\pm7$; $\sigma_{los}^{LL}=128$) for the HL and LL groups respectively. After correcting for rotation, assuming $\langle\Theta\rangle=50$ km s^{-1}, we obtain ($\langle W\rangle^{HL}=-45\pm6$; $\sigma_{los}^{HL}=112$) and ($\langle W\rangle^{LL}=55\pm7$; $\sigma_{los}^{LL}=128$). These results go in the direction marked in fig. 1, clusters with low luminosity move, onn average, towards the NGP while clusters brighter than $M_V=-7.5$ show a negative mean W component.

In addition the second and third items noted above clearly show that both luminosity groups occupy different volumes in the velocity space. They can be distinguished by the centroids of the distributions as well as by the main axes of the dispersion ellipsoids. As noted above, Hartwick (1996) pointed out that the metal-poor GCs display different dispersion tensors for objects located within and beyond the solar galactocentric radius. The inner clusters show a dispersion tensor highly inclined with respect to the Galactic rotation axis while the outer group is almost aligned with the Galactic symmetry axes. Could our results and the results of Hartwick represent different aspects of the same phenomenon?. If this hypothesis is correct then luminosity and galactocentric radius should correlate in the sense that Low Luminosity clusters should be preferentially located in the inner Galactic regions. However, this does not appear to be the case. Our sample does not show any correlation between integrated absolute magnitude and galactocentric radius and we extend this conclusion to the entire Galactic system of GCs (McLaughlin 2000). Therefore the connection between kinematics and luminosity stressed in this work can not be accounted for only by different episodes of cluster formation in distinct gravitational potentials. We must devise another mechanism that is mainly driven by luminosity.

McLaughlin (2000) recently showed that globular clusters fit a plane in the parameter space defined by binding energy, luminosity and galactocentric radius. It was suggested that this relationship is primordial. Our correlation between the vertical velocity component of the GCs and the same two variables (luminosity and galactocentric radius), gives rise to the possibility that this correlation is also primordial or that it reflects destructive processes that have occurred since the halo formation. We do not have a definite answer to this question, but our analysis suggests that "external" variables, such as the orbital parameters (location in the velocity space) are intimately connected with "internal" parameters such as the binding energy and/or luminosity.

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References

Arnold R., Gilmore G., 1992, MNRAS, 257, 225
Burkert A., Smith G.H., 1997, ApJ, 474, 15
Capuzzo-Dolcetta, R., 1993, ApJ, 415, 616
Chen B., 1998, ApJ, 495, L1
Côté P., 1999, AJ, 118, 406
Dinescu D.I., Girard T.M., van Altena W.F., 1999, AJ, 117, 1792 (DGA)
Dionidas S.P., Beers T.C., 1989, ApJ, 340, L57
Elmegreen B.G., Efremov Yu.N., 1997, ApJ, 480,235
Fall S.M., Rees M.J., 1988, in: The Harlow-Shapley Symposium on Globular Cluster Systems in Galaxies (126th IAU Symposium), Dordrecht, Kluwer Academic Publishers, p. 323
Fritze von Alvensleben, 1999, A&A 342, L25
Harris W.E., 1996, AJ, 112, 148
Hartwick F.D.A., 1996, in: Formation of the Galactic Halo — Inside and Out (ASP Conference Series, 92), eds. H. Morrison, A. Sarajedini, ASP San Francisco, p. 444
Hartwick F.D.A., 2000, AJ, 119, 2248
Larson R.B., 1996, in: Formation of the Galactic Halo — Inside and Out (ASP Conference Series, 92), eds. H. Morrison, A. Sarajedini, ASP San Francisco, p. 241
McLaughlin D.E., 2000, ApJ, 539, 618
Majewski S.R., Munn J.A., Hawley S.L., 1996, ApJ, 459, L73
Majewski S.R., Patterson R.J., Dinescu D.I., et al., 2000, in: The Galactic Halo: From Globular Cluster to Field Stars (Proceedings of the 35th Liege International Astrophysics Colloquium), eds. A. Noels et al., Institut d'Astrophysique et de Geophysique, Liege, p. 619
Morrison, H., Flynn, C., Freeman, K. C., 1990, AJ, 100, 1091
Norris, J.E., 1986, ApJS, 61, 667
Poveda A., Allen C., Schuster W., 1992 in: The Stellar Populations of Galaxies (149th IAU Symposium), eds. B. Barbuy, A. Renzini, Kluwer Academic Publishers, Dordrecht, p. 471
Sommer-Larsen J., Christensen P.R., 1987, MNRAS, 225, 499